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Application of Multi-material 3D printing for improved functionality and modularity of open source low-cost prosthetics – A case study

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1 Background

Low-cost 3D desktop printing, although still in its infancy, is rapidly maturing, with a wide range of applications. With its ease of production and affordability, it has led to development of a global maker culture, with the design and manufacture of artefacts by individuals as a collaborative & creative hobbyist practice. This has enabled mass customization of goods with the potential to disrupt conventional manufacturing, giving more people access to traditionally expensive products like prosthetics and medical devices [1], as is the case with e-NABLE, a global community providing open source prosthetics for people with upper limb deficiencies.

However one of the major barriers to proliferation of 3D printing as a major manufacturing method is the limitation of compatible materials for use with the technology [2]. This places constraints on the design approach, as well as the complexity & functionality of artefacts that can be produced with 3D printing as compared to traditional manufacturing methods. As a result, devices like the e-NABLE Raptor Reloaded prosthetic hand, which is designed specifically to be produced via a single extruder FDM desktop 3D printer, have limited functionality as compared to conventional prosthetics, leading to low active use and prosthesis abandonment [3]. However, with the advent of multi-material desktop 3D printing, and increasing availability of a broader range of compatible materials (of varying characteristics) [2], there is scope for improving capabilities of low-cost prosthetics through the creation of more sophisticated multi-material functional integrated devices.

This work documents the exploration of potential applications of multi-material 3D printing to improve production, capabilities and usability of low-cost open source prosthetics. Various material combinations were initially studied and functional enhancements for current 3D printed prosthetics were prototyped using key material combinations identified. Further, a user-centered design approach was utilized to develop a novel multi-material anthropomorphic prosthetic hand 'ex_machina' based on a modular platform architecture, to demonstrate the scope for reduced build complexity and improved dexterity & functional customization enabled by dual extrusion FDM desktop 3D printing. A full prototype was built & tested with a lead user, and results analyzed to determine scope for optimization.

2 Methods

Based on literature review of state-of-art in multi-material 3D printing and 3D printed prostheses, a roadmap was created to link potential prosthetic capabilities with material requirements and capabilities of multi-material FDM desktop 3D printers (Fig. 1). 5 classes of dual material combinations were derived based on comparison of properties and applications of the individual materials. A preliminary material characterization study was undertaken for 12 material combinations using dual material calibration models, printed on an Ultimaker 3 dual extrusion FDM desktop 3D printer (by Ultimaker B.V., Geldermalsen, Netherlands).

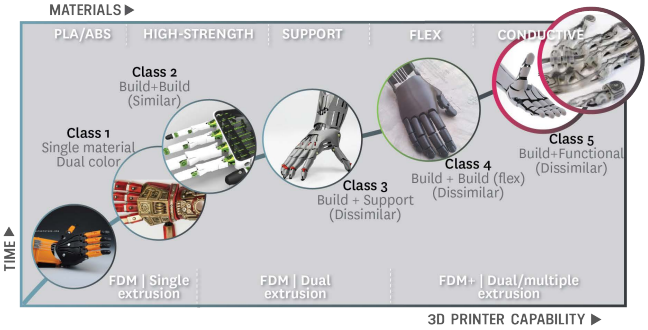

Fig. 1: Roadmap for 3D printed prosthetic devices as a function of material properties and 3D printer capabilities

Based on print performance, compatibility and potential applications, 2 classes were picked for exploring enhanced capabilities for e-NABLE prostheses, namely, Structural + Flexible build materials (Polylactic Acid (PLA) & Thermoplastic Elastomer (TPE)), and Structural + Functional materials (PLA & Conductive/thermochromic PLA). These material combinations were utilized to prototype functional enhancement concepts for current e-NABLE hand designs, in order to assess feasibility and scope of possible multi-material applications for 3D printed prostheses (Fig. 2).

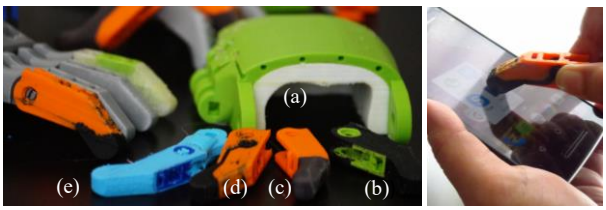

Fig. 2: (Left) Functional enhancements prototyped with the key dual material combinations: (Clockwise from top right) a) custom palm inner soft TPE padding to fit user's residual arm; b) Reinforced tendon pegs (green) for increased durability; c) thermal sensing tip; d) capacitive touch finger; e) soft TPE outer skin for fingertips. (Right) 3D printed Fingertip operates smartphone touchscreen with capacitive sensing (conductive PLA tip)

Further, in order to establish user requirements for 3D printed prosthetic hands, their functionality in the context of day-to-day activities was studied via semi-structured user interviews and observational study. Activities were broken down and categorized according to their constituent dexterity functions [4] (key functions were found to be power, lateral pinch and chuck pinch grips). Current e-NABLE wrist-powered prostheses that work on the principle of single degree-of-freedom (DOF) actuation (i.e. rotation of user's wrist causes actuation of prehensors), were found to be inadequate for prolonged use due to their limited dexterity. This was primarily due to their palm geometry (digit

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placement optimized mainly for power grip) resulting in the lack of a true opposable thumb. Hence based on biomechanics principles, an anthropomorphic palm geometry was used to develop a modular palm design with digit placement and joint orientations optimized to achieve the key required dexterity functions. While for the purposes of this work single DOF actuation was retained (a 160% e-NABLE 'Phoenix' gauntlet with whippletree mechanism was used), additional DOFs enabled either by manual or mechatronic control can increase hand dexterity through utilization of the full potential of an anthropomorphic geometry to support more gestures & grips.

A PLA-TPE integrated finger design was developed with a flexible joint printed with TPE (Ninjaflex (Ninjatek)-15% infill/ Filaflex (Recreus)-100% infill) together with the PLA phalanx and fingertip in one print job. This eliminates the need for fasteners/pins typically required for assembly, and tensioners required for prehensor disactuation.

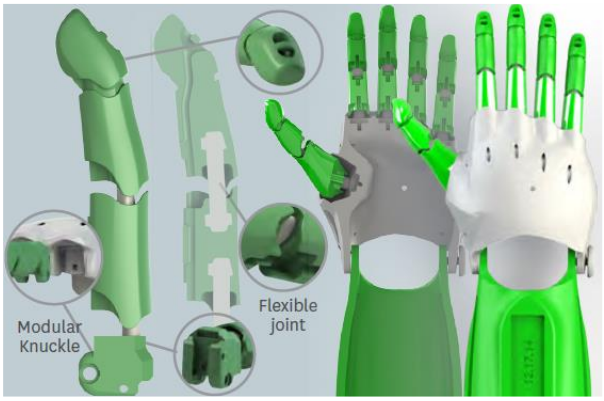

Fig. 3: (Left) Integrated finger (PLA body + TPE joints) docks with palm and is easily removable, enabling modularity & easy maintenance; (Right) ex_machina assembly w/ anthropomorphic palm geometry & opposable thumb.

3 Results

The build & function of ex_machina was evaluated against current e-NABLE devices (Raptor Reloaded/Phoenix) (Fig. 4). Actuation force required for the PLA-TPE integrated finger was measured via strain gage and found to be lesser in comparison to that of a Phoenix finger (3.5N vs. 5.3N).

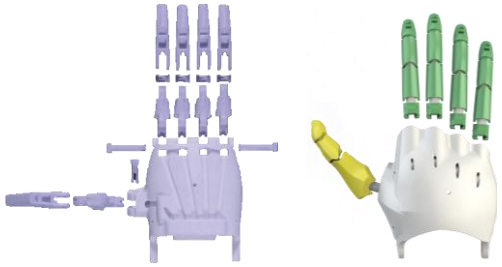

Fig. 4: The modular ex_machina terminal device (right) (6 parts and 5 assembly steps) as compared with the e-NABLE Raptor Reloaded (left). (19 parts and 8 assembly tasks) enables reduced complexity of build, and easier maintenance.

The key dexterity functions were tested subjectively with a lead test user (adult male, with residual right palm). Good chuck and lateral pinch functions were observed. Power grip was found to be limited due to the approach trajectory of the thumb around the object being gripped. This needs to be further optimized to increase reach and clasping efficiency of a power grip in the absence of multi-DOF digit actuation.

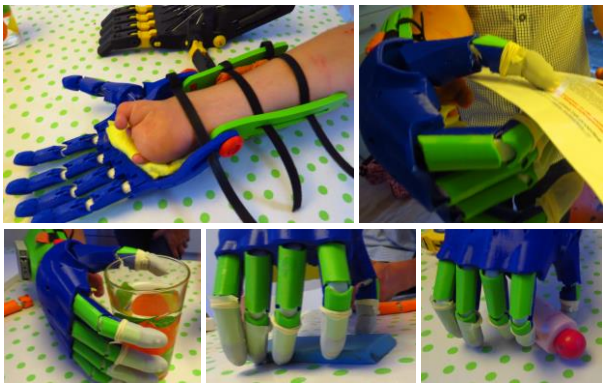

Fig. 5: (Clockwise from top left) Fitting user's residual palm into device cavity; Lateral pinch; 3-point chuck pinch; Power grips (sphere and heavy wrap)

4 Interpretation

The ex_machina prosthesis design aims to introduce a shift in low-cost 3D printed prosthetics from a focus on maker-driven design to user-centered design, with the goal of improving quality of life of users. This requires improved functionality of such devices in the context of day-to-day tasks, which can be achieved via complex active/passive functional systems enabled by multi-material desktop FDM 3D printing. In ex_machina, the use of TPE joints in combination with PLA finger structure, along with an anthropomorphic palm geometry, facilitates key dexterity tasks through more natural 'human-like' digit motion. TPE was further utilized to develop soft skins, grips and custom paddings to improve ergonomics & tactile experience, to supplement strength & rigidity of the digit's PLA structure. Functional enhancements like the sensing fingertips were proven to provide additional value to 3D printed prosthetics via the use of functional materials. However focus should be on developing such enhancements not as novelty applications but to enhance usability through increased capability of the device over and above the basic dexterity requirements.

Future work provides scope for user-centered design framework within e-NABLE R&D based on a modular platform design, wherein functional enhancements can be developed independently as modular attachments to a basic optimized anthropomorphic device architecture. This would help integrate the efforts of the maker community to efficiently and quickly deploy new multi-material 3D printed functions/capabilities to the existing e-NABLE portfolio of 3D printed prosthesis designs, in order to meet individual user requirements through increased customization and adaptability.

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